Thermal Management and Deployment of a Thin-walled Enclosure for a High-temperature Superconducting Coil

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Objectives & Applications

The design must allow for

- Full enclosure of high-temperature superconducting (HTS) coil
- Compact stowage method so an enclosure of 20-meter major diameter can be stored inside a 5-meter payload fairing during launch
- Ability to deploy from a stowed state after delivery to orbit
- Thermal management system capable of keeping the coil below the HTS critical temperature to maintain material's zero-resistance properties
- Debris or minor puncture mitigation

Two or more HTS coils will generate a large electromagnetic field for the purpose of

1. Actuating spacecraft in a cluster or spacecraft components using force from interacting magnetic dipoles
2. Wireless power transfer between spacecraft in a cluster using resonate inductive coupling
3. Radiation and high-energy charged particle shielding by configuring stacks of coils around spacecraft including spacecraft for human flight missions

Background

1. Actuation of coils
   - Ground testing of two pairs of orthogonal HTS coils moving on a flat floor
   - Microgravity six (6) degree of freedom testing of two non-superconducting coils inside the ISS in conjunction with the SPHERES facility
   - Rigid loop heat pipe testing inside vacuum chamber
2. Resonant inductive coupling power transfer
   - Characterization of oscillatory field generated by HTS coil cooled using liquid nitrogen submersion
   - Demonstration of non-superconducting coils performing power transfer operation in microgravity
   - Development of commercial applications for non-superconducting coils
3. Radiation and high-energy charged particle shielding
   - Numerical and particle simulation coil size and field strength requirements
   - Configurations for creating a null space inside spacecraft for the health and safety of humans

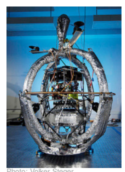
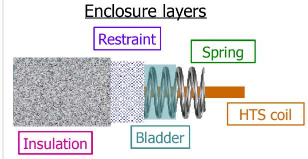


Photo: Volker Steger

Photo: NASA

Design



Fabricated test article

A series of compression springs act as primary deployment mechanism while providing cavity and structure for suspending the HTS coil in the chilled vapor space. Polyvinyl chloride collars join the springs so that the segments are straight in the relax deployed state. Nitrogen vapor is contained by the double layer of polyethylene tubing. A continuous bi-weave fiberglass sleeve acts as a restraint layer to reduce stresses on plastic bladder.

Four overlapping panels of multilayer insulation constructed from low density polyethylene fabric and single-sided aluminized mylar simulate the thickness of high performing thermal insulation. The long edges of the panels bow out to allow for a higher compression ratio. The coil can be constructed using a flat tape HTS material.

Cross-section of HTS tape

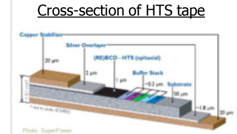
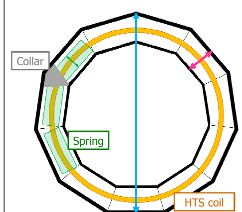
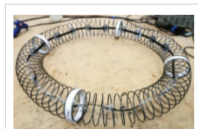


Photo: SuperPower



Summary of Test Article	
Major toroid diameter	1.85 meters
Number of segments	11
Outer minor diameter	17.5 cm
Vapor core diameter	10.3 cm
Number of layers in MLI	6



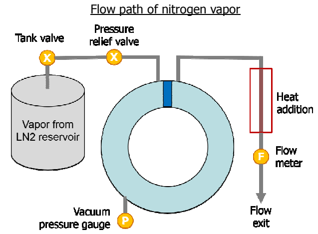
Small-scale concept demonstration of enclosure structure with surrogate coil suspended in spring cavity

Shape of coil in stowed configuration highlighted to show S-curve utilizing the small acceptable radius of curvature of the HTS tape

Thermal Testing & Analysis

Temperature data at limited locations → Apply transient thermal energy model → Find material properties using least squares fit → Validate model by recreating data profile → Complete profile for all locations → Examine other test conditions using same model & material properties

The enclosure was cooled as an *open system with chilled nitrogen vapor* supplied by a high pressure liquid nitrogen tank. The flow exited the system at atmospheric pressure and heated to room temperature before passing through the flow meter due to operational limitations of the meter.



The thermocouples locations were limited by the number of available feedthroughs. Temperature was measured at different layers only at the major circumference midway point. Additional temperature measurements of the bladder outer surface were taken near the inlet and outlet, as well as the 3/4 point around the major circumference.

Same for all segments

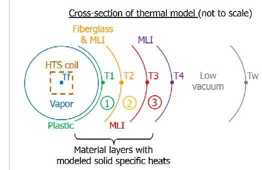
$$\begin{bmatrix}\text{heat from}\\ \text{chamber wall}\end{bmatrix} = \begin{bmatrix}\text{heat into}\\ \text{outermost layer}\end{bmatrix}$$

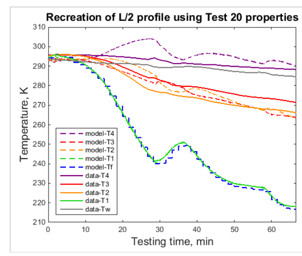
Applies to material layers ① ② ③

$$\left\{\begin{bmatrix}\text{heat into}\\ \text{material layer}\end{bmatrix} - \begin{bmatrix}\text{heat out of}\\ \text{material layer}\end{bmatrix} = \begin{bmatrix}\text{heat stored by}\\ \text{material layer}\end{bmatrix}\right\}$$

$$\underbrace{\begin{bmatrix}\text{heat through}\\ \text{bladder}\end{bmatrix} = \begin{bmatrix}\text{heat extracted}\\ \text{by vapor}\end{bmatrix}}_{\text{Determines flow temperature for downstream segment}}$$

The chamber pressure was limited to a weak vacuum of 30-700 mbar during a test. For this reason, *conduction is assumed to dominate* as the primary mode of radial heat transfer. Axial heat transfer from one segment to another was assumed negligible due to discontinuities in the materials at segment joints.





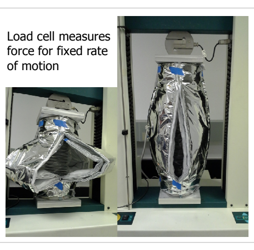
Deployment Demonstration

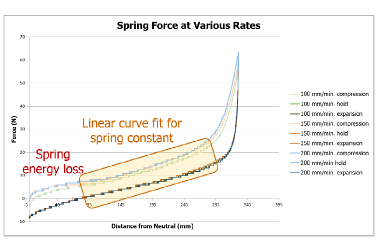
Single straight segment

Axial force measurements were taken for a single spring identical to the springs used in the full toroidal test article. Slow compression and expansion of the spring was used to identify the effective spring constant of the enclosure assembly compared to the factory specified value of the spring alone.

The *effective spring constant nearly doubled* from 0.200 lbs/in to 0.393 lbs/in. (std dev = 0.031) after examining the spring force for three different axial velocities of the load cell.

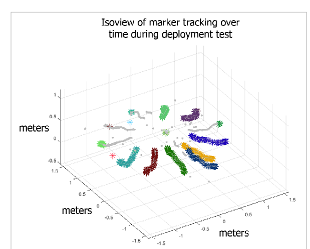
Load cell measures force for fixed rate of motion





Full toroidal enclosure

A motion capture system was utilized to observe the full dynamic deployment of the enclosure. Infrared cameras mounted along the ceiling perimeter of the test space recorded the locations of reflective markers during the deployment motion. The fidelity of the cameras allowed for the characterization of the *bulk expansion motion* as well as *harmonics* during the settling of the enclosure. The marker images can also be used to estimate the *stowage efficiency* of the enclosure.



The analysis identified markers at the full deployed state and works backward in time to track the same markers to the start of the recording. The enclosure was suspended by ropes so the analysis must take into account the effects of rope tension as well as gravity. The results were compared to the conclusions made from the single straight spring testing.

Aluminized mylar coated with black paint to minimize noise and erroneous reflections detected by motion capture infrared sensors